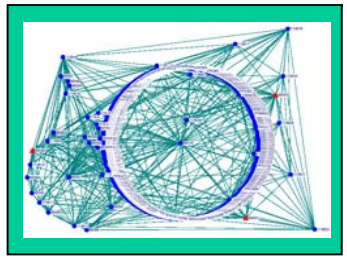
FERMILAB



TeVnet

Surveying the Big Machine

John A. Greenwood, LS

Fermilab Alignment & Metrology Group

Accelerator Physics and Technology Seminar Series

February 28, 2006

Glossary

separated by an uncommon language…

- As we are all well aware, words with seemingly clear meaning to surveyors, may need clarification for physicists, and vice-versa!
- Preanalysis = simulation
- Adjustment = Gaussian fit or best-fit
- Sigma, Uncertainty, Coverage Factor all mean about the same thing.
- Leveling: a method for determining the orthometric height of objects.
- Common expression of precision:
  - Physicist - 1σ
  - Surveyor - 2σ
- Please help expand this list by raising your hand… ☺

TeVnet Overview

- By early ***2003***, it had come to be ***obvious that the Tevatron was under performing.*** The ***Tevatron Alignment Task Force*** was formed. TATF asked for a meeting with the ***Alignment & Metrology Group*** to discuss ***methods*** with which to ***discover the degree of non-compliance of the Tevatron orbit with respect to an <u>Ideal</u> machine.***

What constitutes 'Ideal'

- In the early 1980s, Thornton Murphy and Leo Michelotti, among others, devised a strategy to align the Tevatron. They concluded that it was possible to transfer the alignment of the Main Ring to the Tevatron, after applying certain design considerations. The theoretical location for the Murphy plugs, making up what is called the "Murphy Line System," describes the 'ideal' Tevatron. ***The Murphy Line System was to act as the transfer artifact between the Main Ring and the Tevatron.*** This assumed, however, that the Main Ring orbit was already sufficiently precise in order to properly affect a useful transfer. ***A slide later in this presentation will show the precision of their assumption.*** Had modern surveying equipment such as LaserTrackers and GPS been available, Thornton and Leo may well have chosen a different method.

TeVnet Overview

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- AMG suggested a ***survey conceptually similar to*** that undertaken for the ***Main Injector.***

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- AMG suggested a survey conceptually similar to that undertaken for the Main Injector.
- The ***solution***, now ***known as TeVnet***, *is a* ***coherent three-dimensional reference frame***, ***planned, implemented, and reviewed*** toward the objective of ***improving the operation of the Tevatron.***

TeVnet Overview

- **This presentation will detail the**
  - **Planning**
  - **Implementation**
  - **Analysis**
  - **Results**
  - **Assess the 3D-*shape* of the current machine componentry.**

Acknowledgements

Prime movers

Terry **Sager** & George **Wojcik**

Impetus

Norm **Gelfand**, Ray **Stefanski**, Jim **Volk**
Tevatron Alignment Task Force

Counsel

Bob **Bernstein**

Scrutineers

Gary **Coppola** & Stu **Lakanen**

GPS review

Virgil **Bocean** & O'Sheg **Oshinowo**

Heavy lifters

AMG
Glenda **Adkins**
Craig **Bradford**
Gary **Crutcher**
Ed **Dijak**
Mike **O'Boyle**
Charles **Wilson**
Jean **Wilson**
Randy **Wyatt**

ANL
Bill **Jansma**
Stan **Johnson**
Keith **Knight**
Scott **Peterson**
Scott **Wesling**

BNL
Terry **Mroczkowski**
Charles **Spataro**

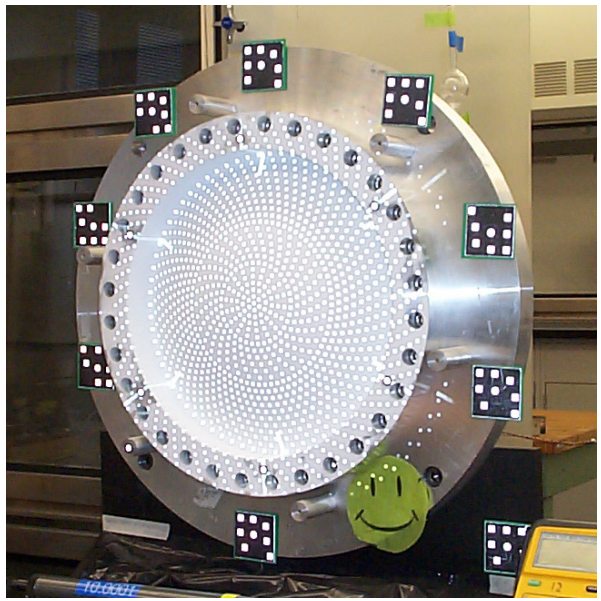
JSS
Larry **Horvath**
Mike **Smego**

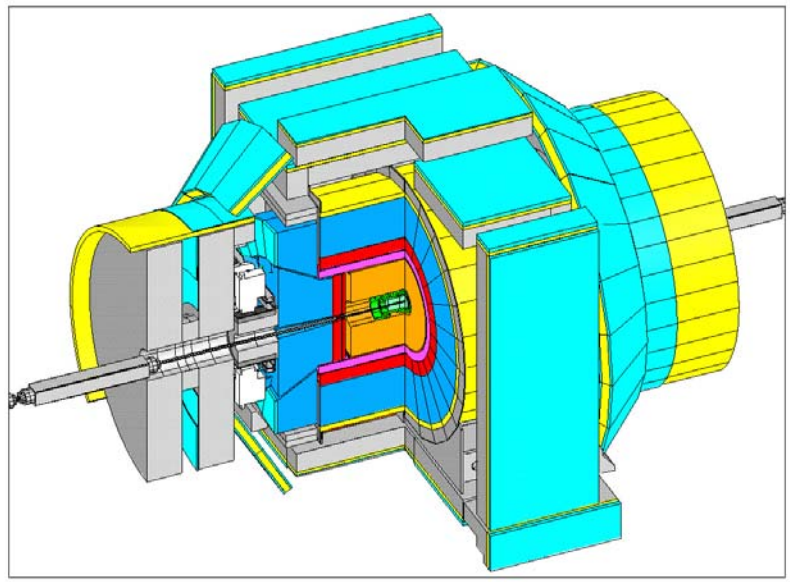
MSC
Dan **Fears**
Ryan **McMahon**
Tom **Mueller**
Purdy **Smith**
Charles **Zwicker**

PPD
Tony **Rodriguez**
Manuel **Seals**
Wayne **Shaddix**
Gary **Teafoe**
Jim **Wish**

SLAC
Cris **Banuelos**
Mike **Rogers**

How big is BIG?





Mucool LH2 Absorber window

~ 30 cm

CDF detector

~ 15 m

Examples of 3D coordinate metrology

How big is BIG?

Boeing 777-ER

~ 75 m

USS Ronald Reagan

~ 320 m

Examples of 3D coordinate metrology

How big is BIG?

Fermilab's
Main Injector
~ 3.3 km
(~π km)
circumference

How big is BIG?

Fermilab's

Tevatron

2π km

circumference

Examples of 3D coordinate metrology

The Tevatron Problem

- ***After extensive upgrades*** to the Tevatron, ***performance and reliability were below expectations.***
- Why? Among several reasons, the ***current alignment method***, known as the **'Murphy Line System,'** ***makes a reliable orbit, at increased energy levels, much more difficult to obtain***.

The Solution

- Bring ***modern metrology methods and instrumentation**** to the alignment of the Tevatron.
- LaserTrackers* in ***network mode***
- GPS* using a ***highly redundant array of receivers***
- ***Robotic**** angle measurements
- Install ***ultra-stable*** Deep Rod Monuments* (DRM)

* more later

Background

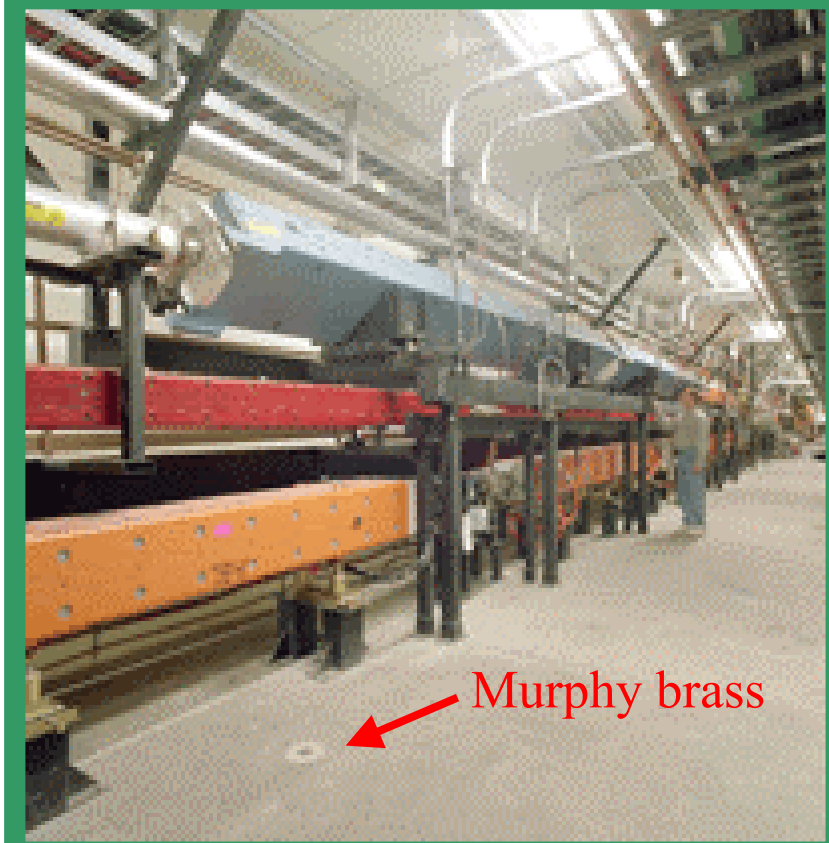
- What is the Tevatron?

Background

- What is the Tevatron?
- ***A 6.3-km circumference, 1 Trillion electron-volt proton-antiproton accelerator which is used to study the fundamental aspects of nature.***

Background

- What is the Murphy Line system?



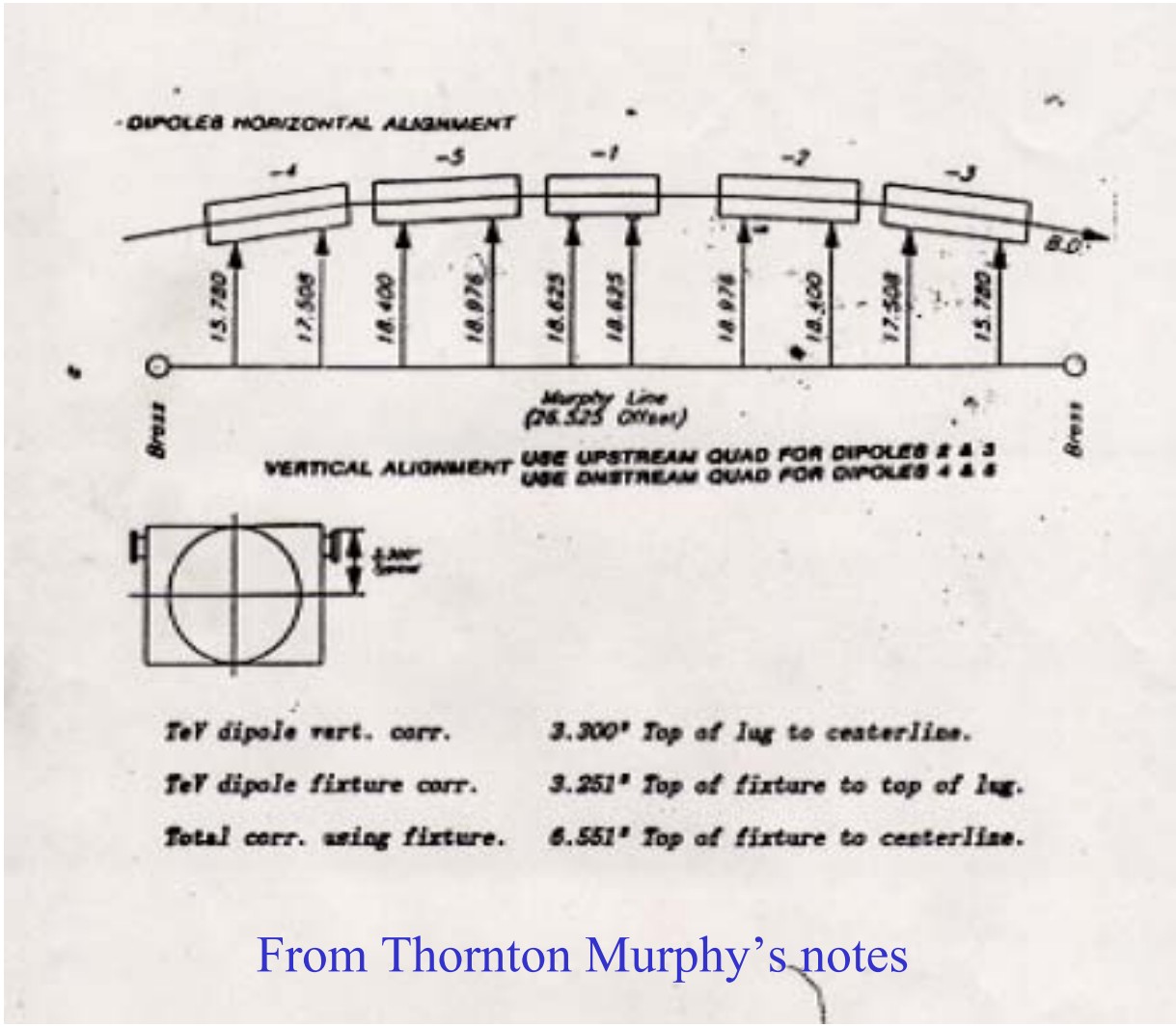
Background

- What is the Murphy Line system? ***A series of 200 <u>unconnected</u> tangent-offset lines, inscribed by the the Tevatron magnet array.***

Background

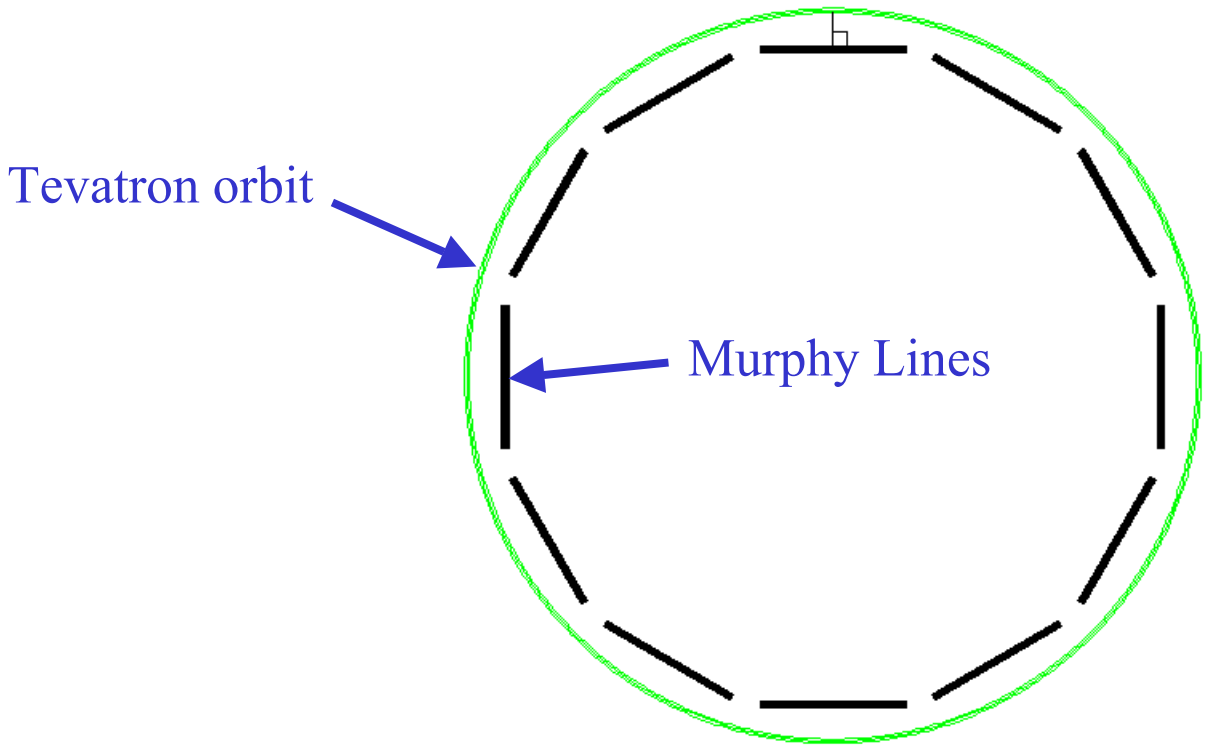
- What's wrong with Murphy's lines? ***Orbit shape is poorly controlled*** *because each line* ***constrains the alignment of only five local magnets.***

Murphy Line



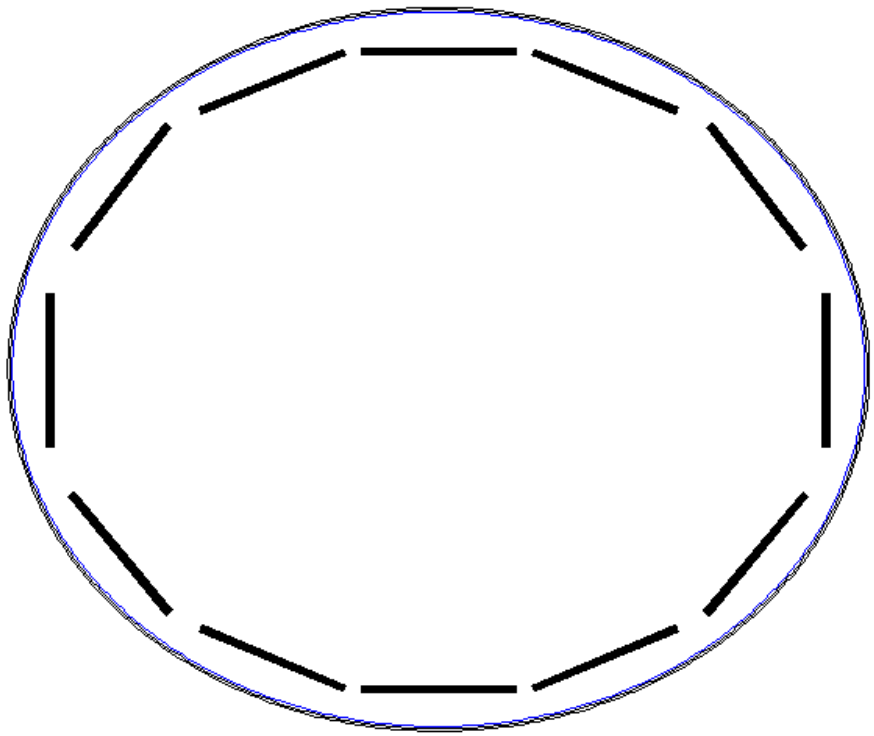
From Thornton Murphy's notes

Ideal Murphy Line Orbit

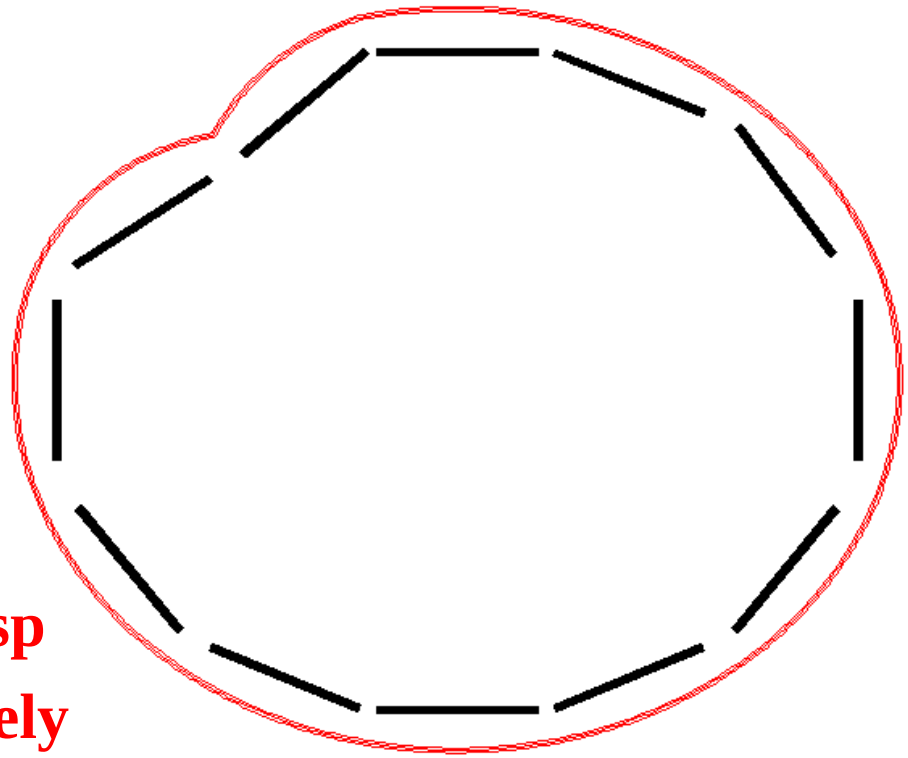


Actually a 200-sided quasi-polygon

Possible Murphy Line Orbit



Probable Murphy Line Orbit



In reality, the cusp shown here is likely for all 200 Murphy Lines.

TATF's Initial Request

- ***Survey*** the Murphy *brass*, ***establishing coordinates for each of the brass plugs*** defining the 200 Murphy Line segments.

TATF's Initial Request

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- Requested method: Holding the site ***coordinate system origin fixed***, ***traverse around the ring*** and tie in each Murphy plug. ***Desired precision < 2.5mm (1σ), as measured across the ring – 2,000m!***

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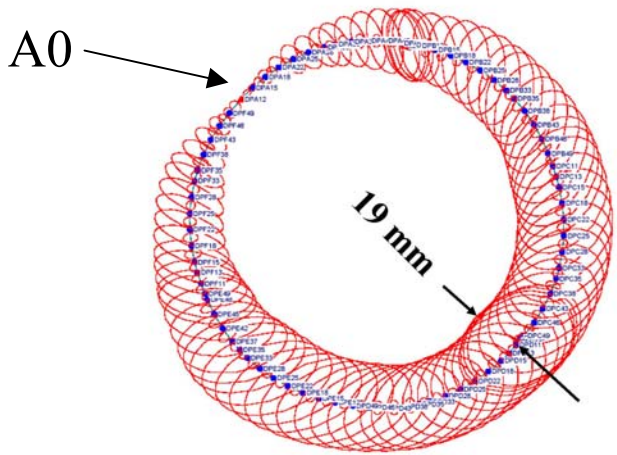
- **Why won't this work?**

Murphy Line Traverse Preanalysis

Murphy Line Traverse, Coordinates Fixed at A0



Requested method

Figure 1

Not Good Enough

Suggested Remedies

- Open existing sight risers at C0 and F0
- Add new sight risers every ~300 meters!

Not Good Enough

Suggested Remedies

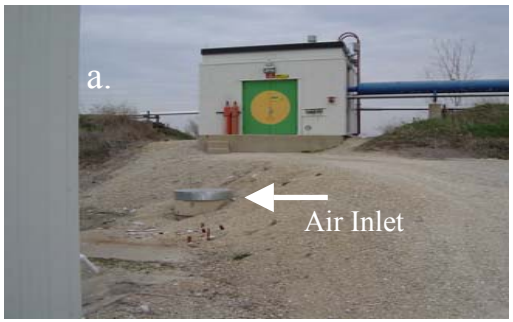
- Open sight risers at two available locations
- Add sight risers every ~300 meters!
- Response: **$$$$ Yikes!!!**

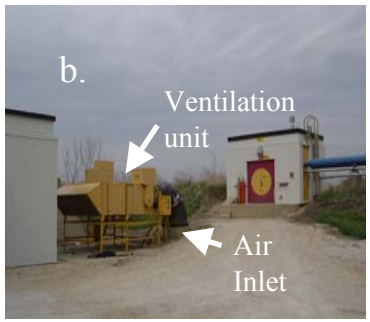
Not Good Enough

Suggested Remedies

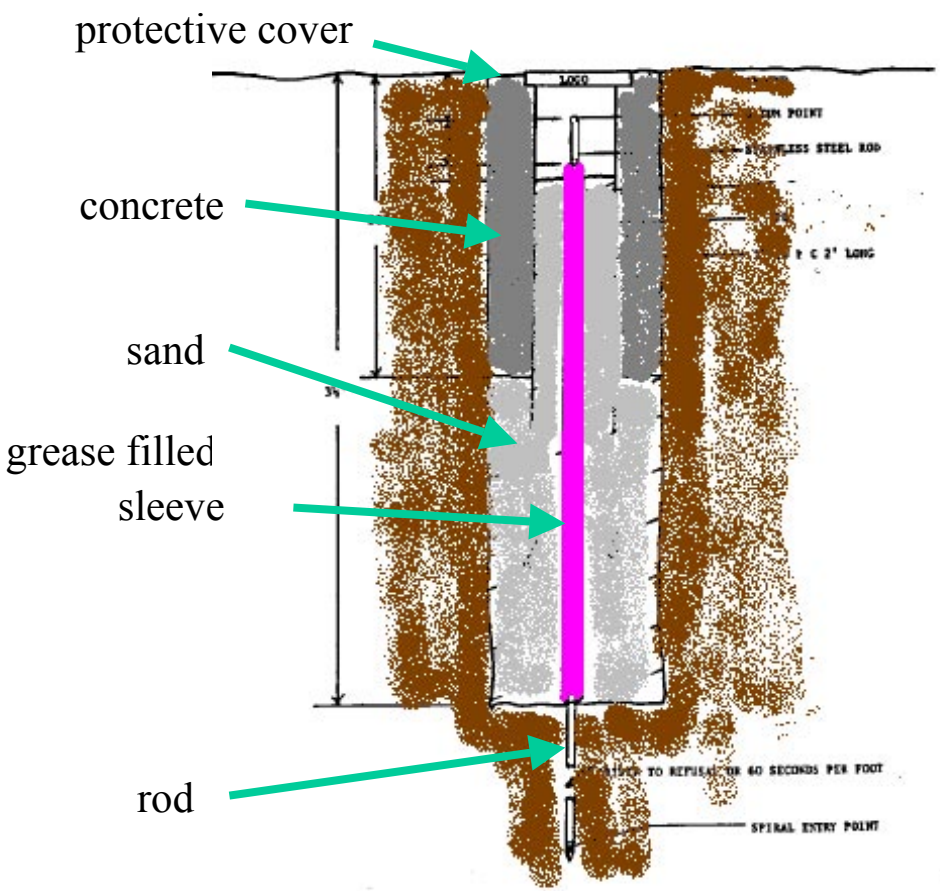
- Open sight risers at two available locations
- Add sight risers every ~300 meters!
- Response: **$$$$ Yikes!!!**
- Compromise: ***Implement 12 new sight risers (~ 500 meters), plus opening two existing sight risers***

Sight risers





Deep Rod Monument (DRM)



¾” Al. rod driven to refusal - 12-25m locally

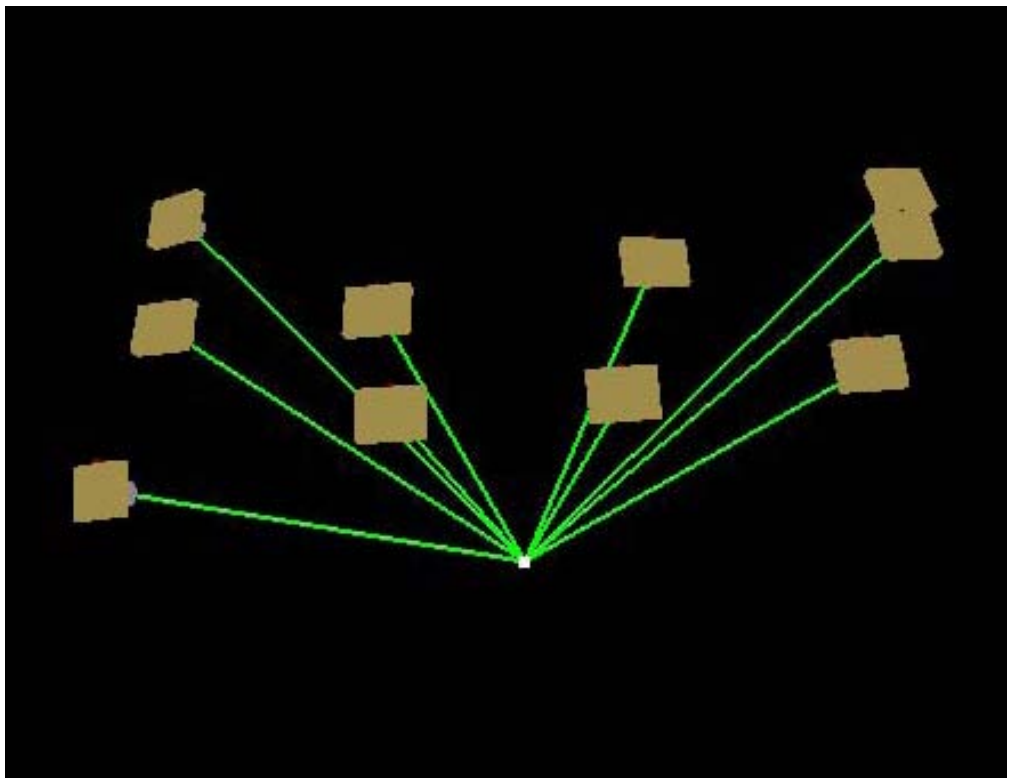
Develop a surface network

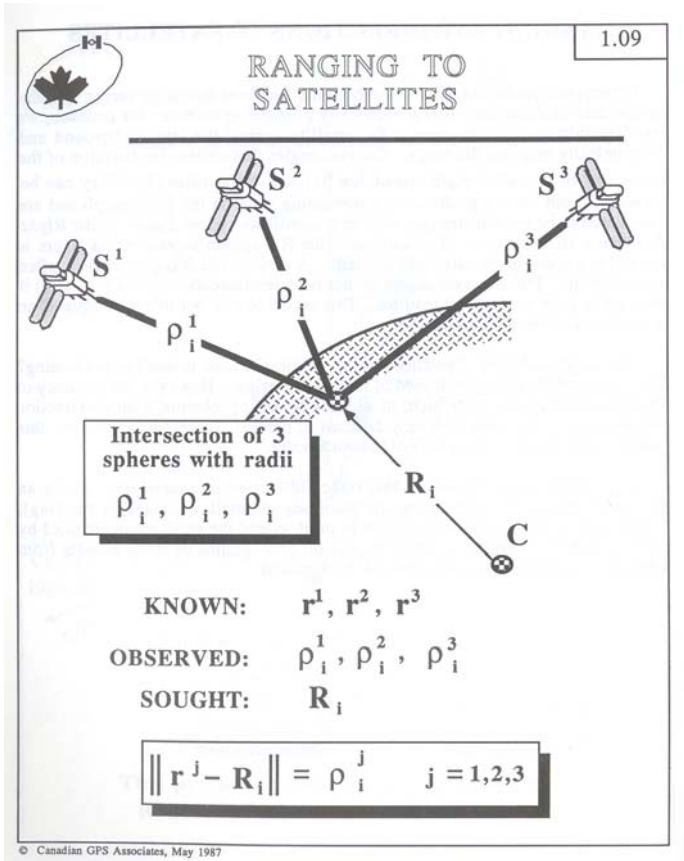
- Control positions of sight risers by a ***redundant array of seven GPS receivers*** deployed for 90-120 minute sessions.
- ***Measure laser distances*** between ***sight risers*** and ***DRM***.
- ***Level*** through DRM and sight risers
- ***Include adjacent elements of accelerator complex***

How does GPS work?

- Backpacker mode – **NOT!**
- Navigation mode – **NOT!**

Backpacker GPS

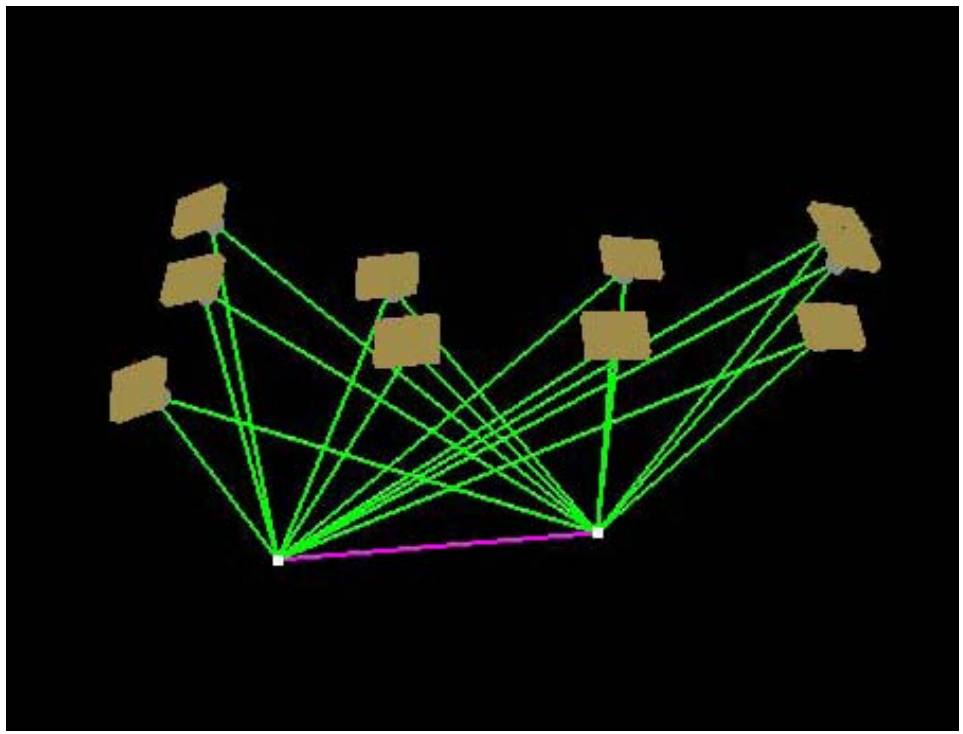




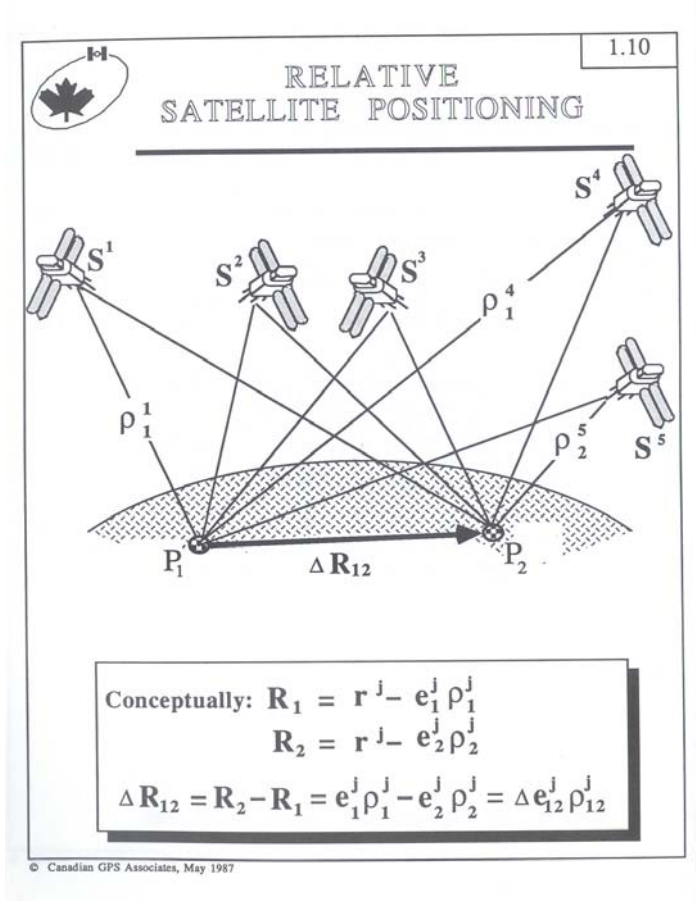
How does precise GPS work?

- Backpacker/navigation mode – accuracy 2-10m
- **Surveyor (precise) mode**

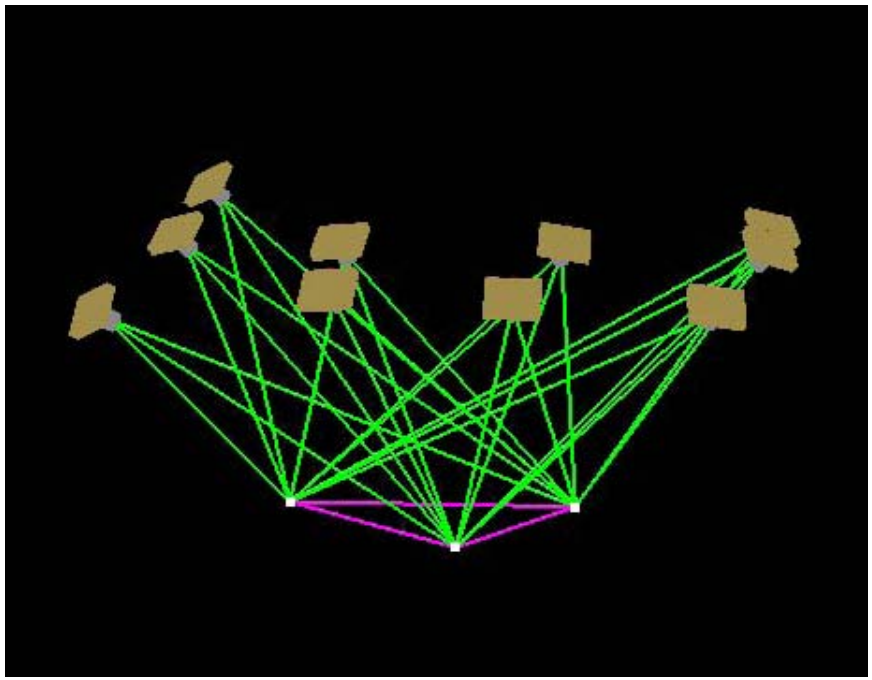
How does precise GPS work?



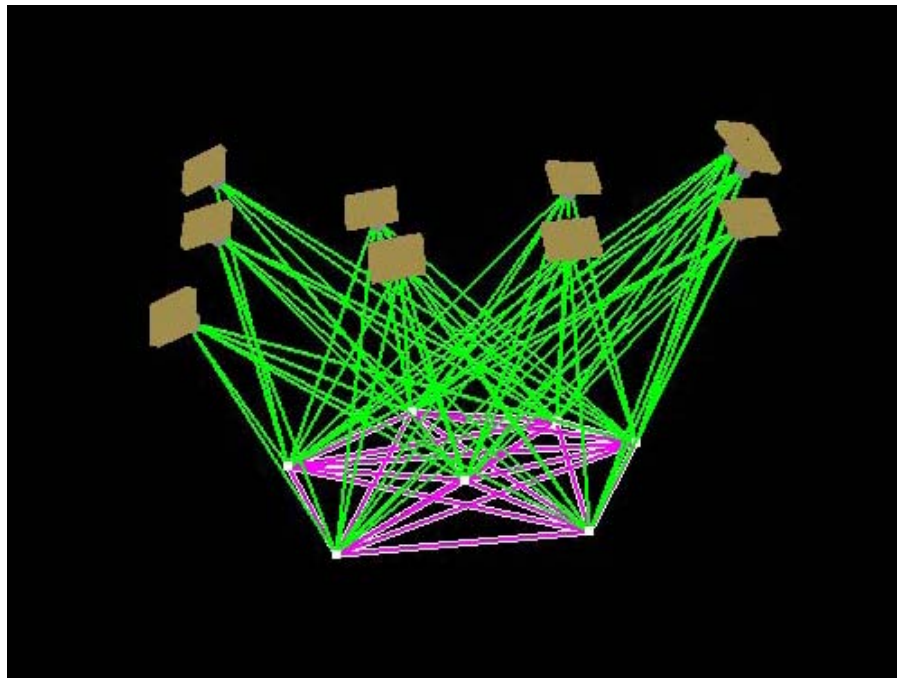
Two receivers



How does precise GPS work?

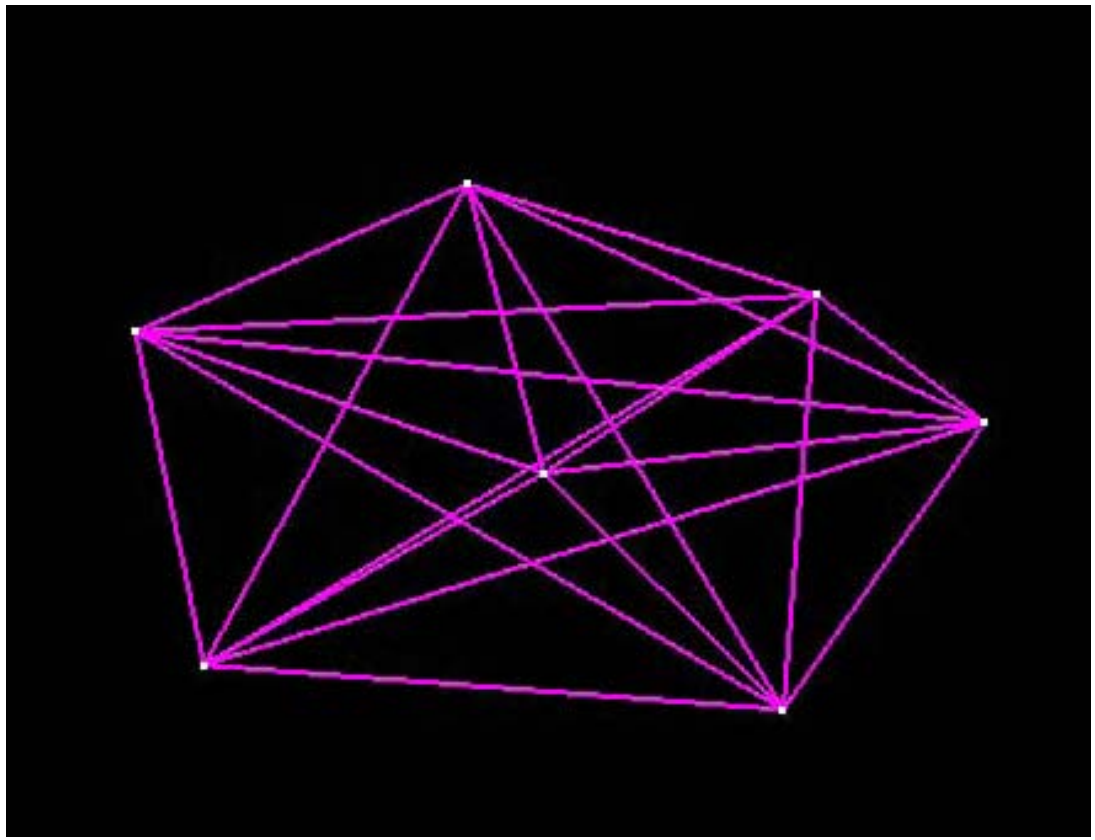


Three receivers



Seven receivers

What you get precise from GPS



$\Delta X, \Delta Y, \Delta Z$

For all baselines combinations, expressed in the global reference frame

One session yields 21 3D-baselines

New GPS antenna

- Backpacker/navigation mode – precision 2-10m
- Geodetic mode – As used in *TeVnet*, ***precision from GPS is limited by antenna design and signal multi-path issues.*** Antennas used in *TeVnet* have phase-center precision of ***0.5mm***; employs ***stealth*** technology to provide high multi-path rejection.

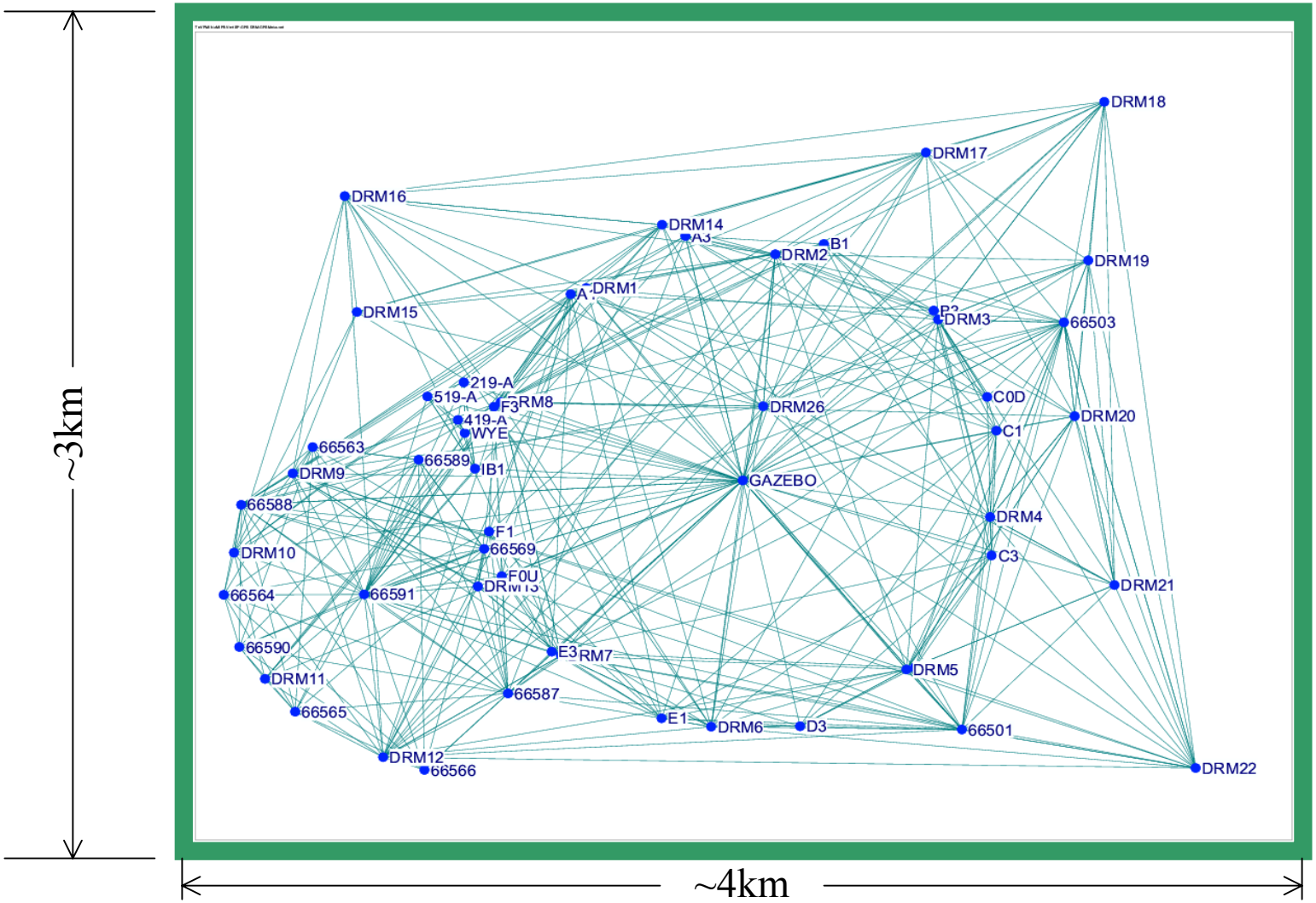
GPS Equipment

Trimble Zephyr Geodetic
antenna with 5700 receiver

Trimble Zephyr Geodetic
antenna on concrete pier

Surface network design

GPS + laser distances + leveling



Tunnel Traverse + GPS

14 Sight Riser Surface Network Preanalysis

GPS + Traverse

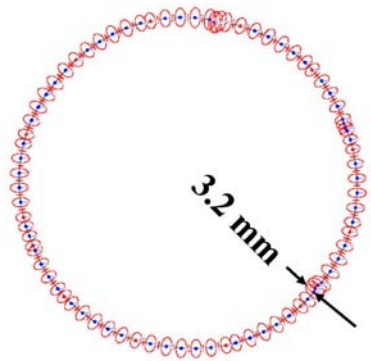


Figure 2

It's still not good enough!

- What to do? ***Add LaserTracker tunnel network using Tracker in network mode***

LaserTracker

- What is a LaserTracker?
- How does it work?
- What are its limitations?

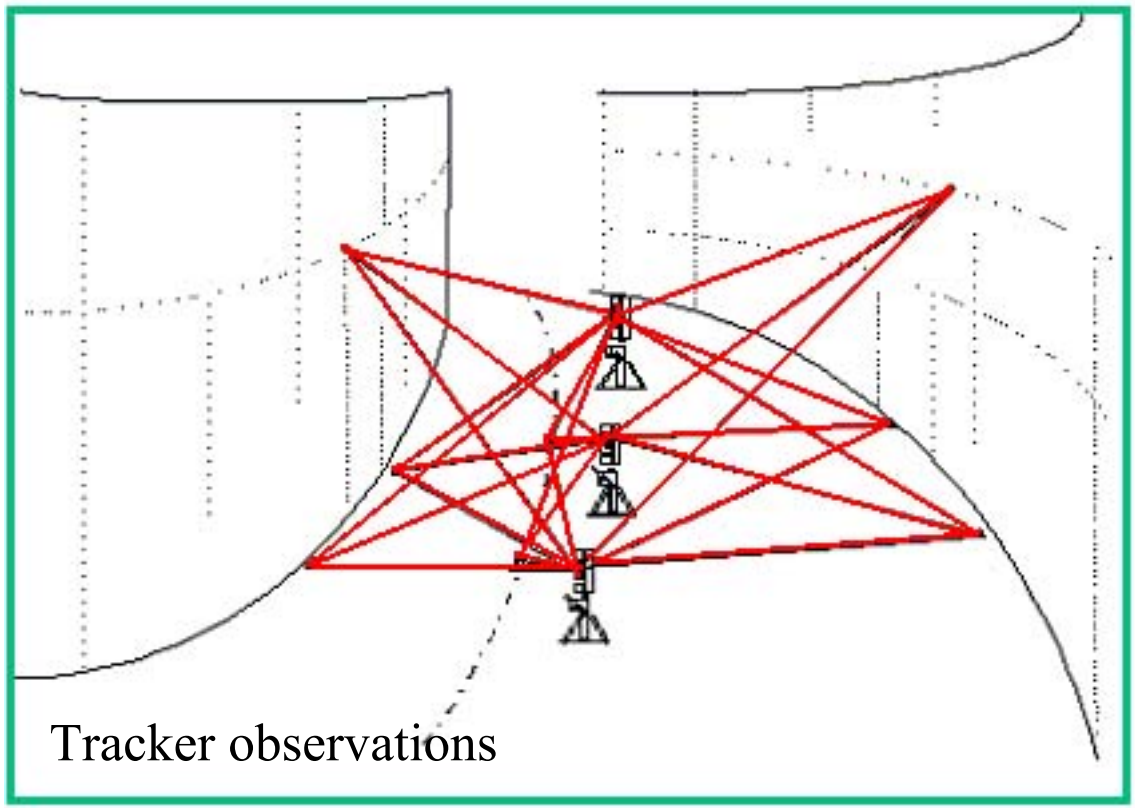
API LaserTracker

3D spatial accuracy: 5ppm (2σ) for range up to ~ 40m

LaserTracker*II* plus

1.5” spherically mounted reflector

LaserTracker in network mode



LaserTracker 'derived chords'

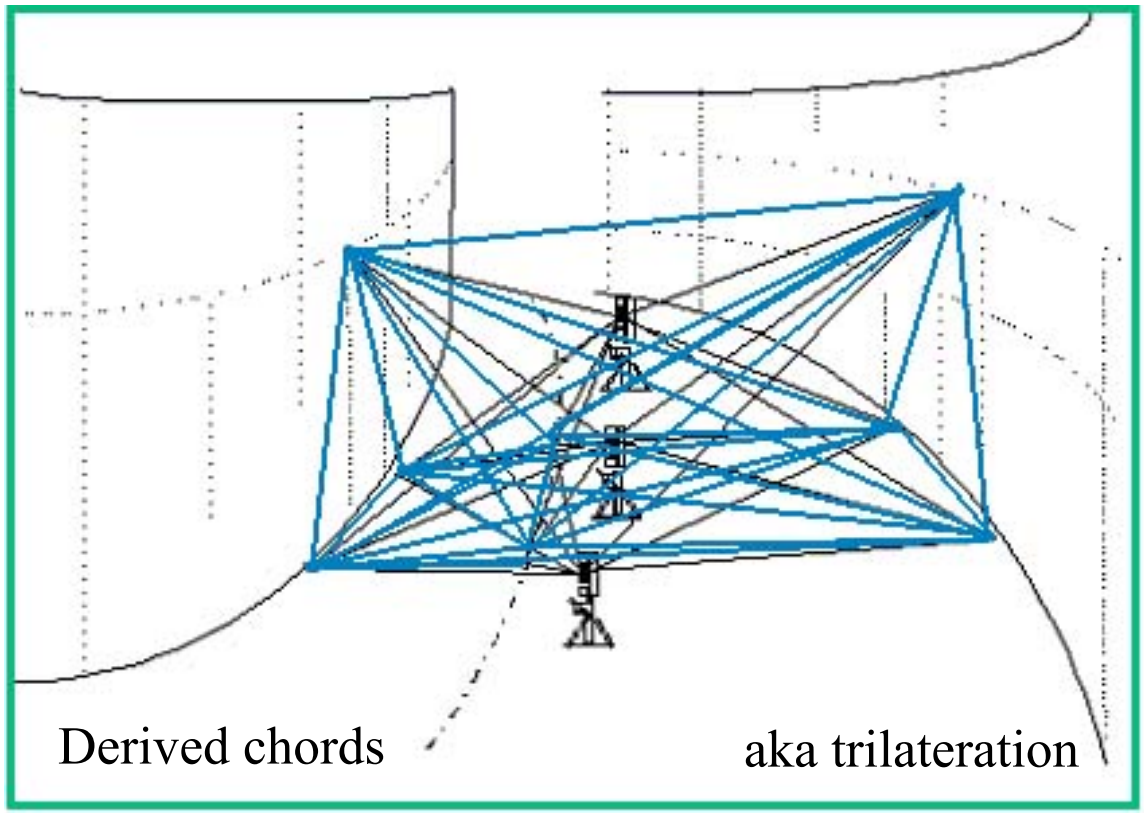
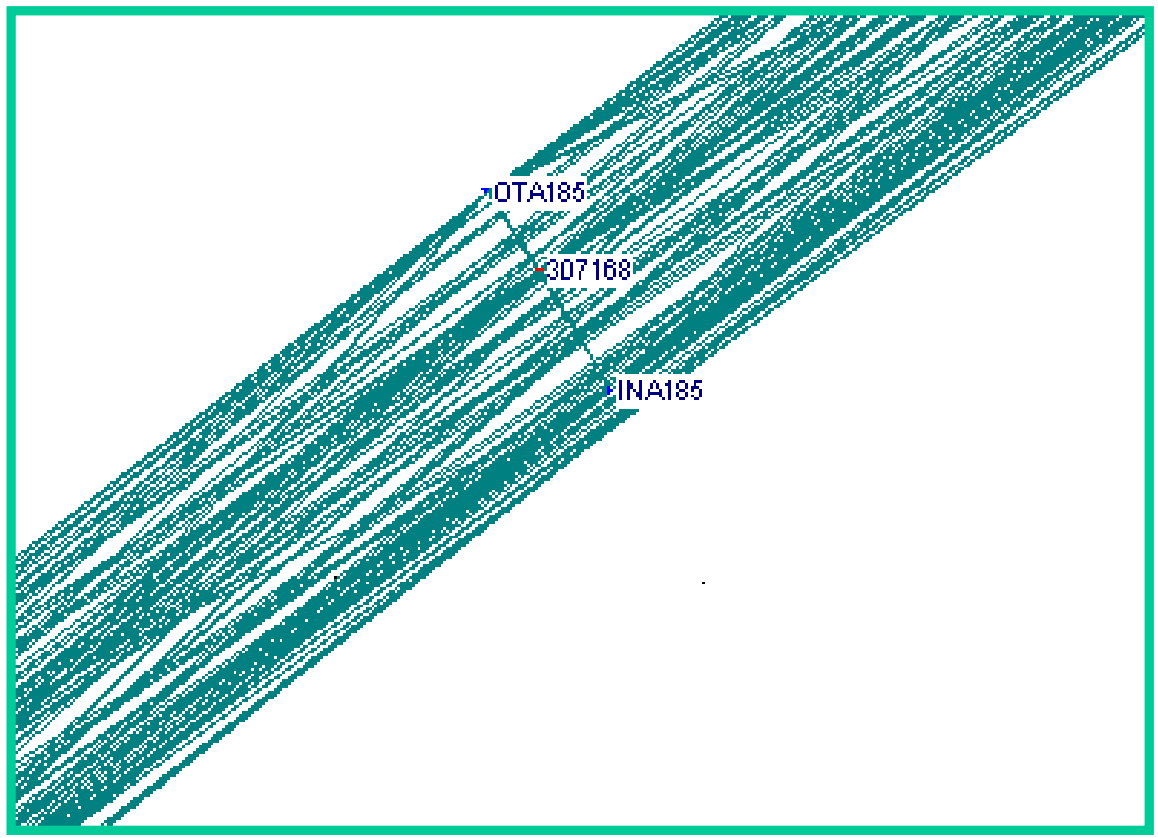


Diagram represents a very small percentage …

LaserTracker 'derived chords'



Actual derived chords from ***TeVnet*** survey

LaserTracker 'derived chords'

- What are the advantages? ***The number of effective observations is reduced by ~60%. Self-checking via high redundancy.***

LaserTracker 'derived chords'

- What are the advantages? The number of effective observations is reduced by ~60%. Self-checking via high redundancy.
- What are the limitations? *With trilater-ation,* ***all shape control is lost because there is no remaining angle information included in the Tracker data to constrain the network.***

LaserTracker 'derived chords'

- What are the advantages? The number of effective observations is reduced by ~60%
- What are the limitations? With trilateration, all shape control is lost because there is no remaining angle information included in the Tracker data to constrain the network.
- Why use *derived* chords? ***Existing soft-ware limits the number of observations, thereby limiting the network design strategy.***

Is it good enough yet?

- What to do? Add LaserTracker tunnel network using Tracker in network mode.
- ***Add precise level network in the tunnel***

Full Network Preanalysis

GPS + LT + Traverse + Levels + Gyro-azimuth

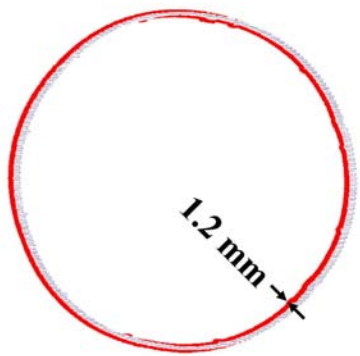


Figure 3

Can the network be leaner?

- What happens if we use **only the Laser Tracker**?
- **Major loss of *shape* control**.

LaserTracker Only Preanalysis

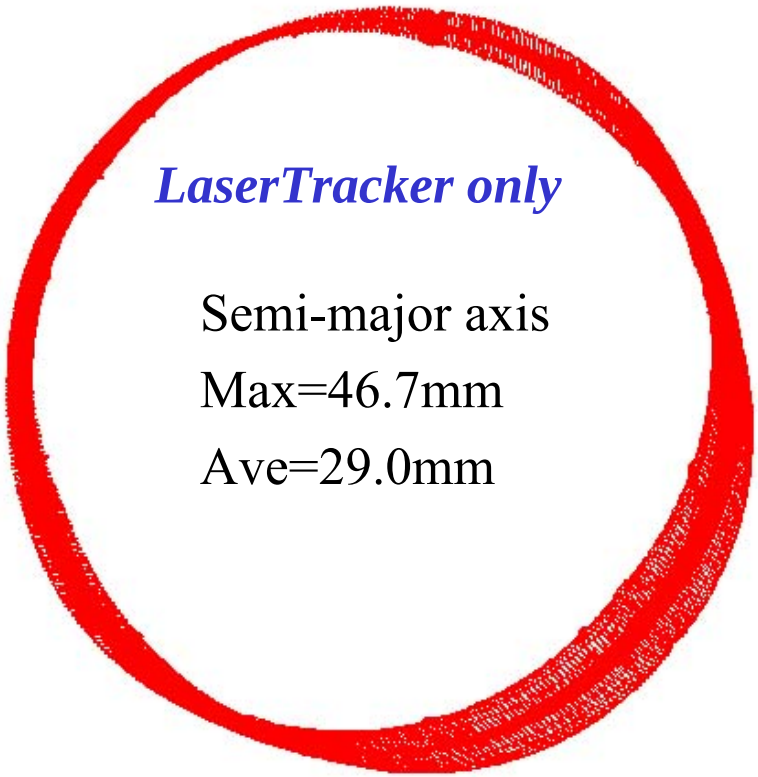


Figure 4

Can the network be leaner?

- What happens if we **remove the surface network** – use Laser Tracker + Murphy Line Traverse?
- Moderate loss of *shape* control.

LaserTracker + Traverse Preanalysis

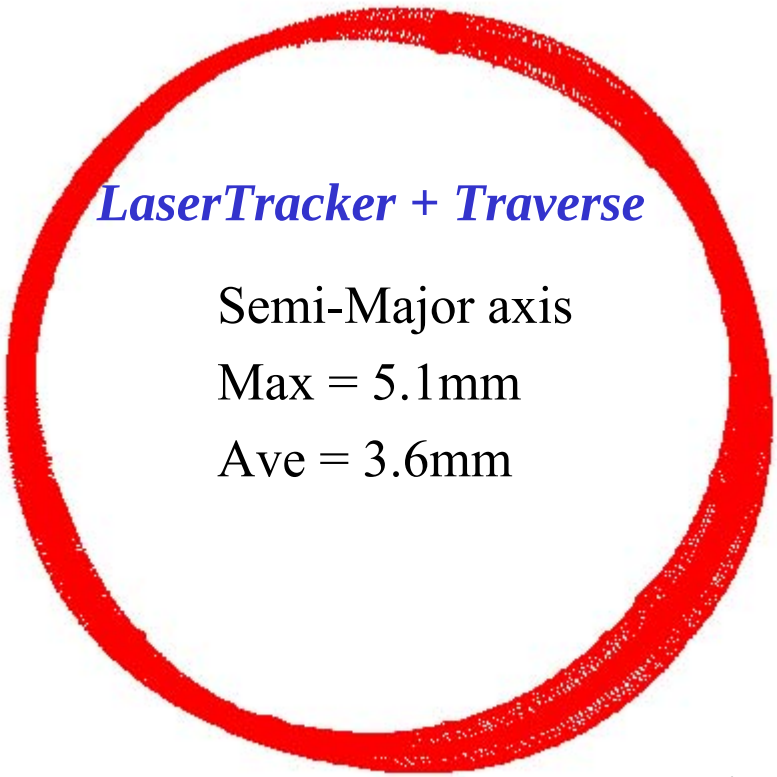


Figure 5

Can the network be leaner?

- What happens if we **remove the Murphy Line Traverse** – Laser Tracker + surface network?
- **Loss of *shape* control between sight risers**.

Surface network + LaserTracker Preanalysis

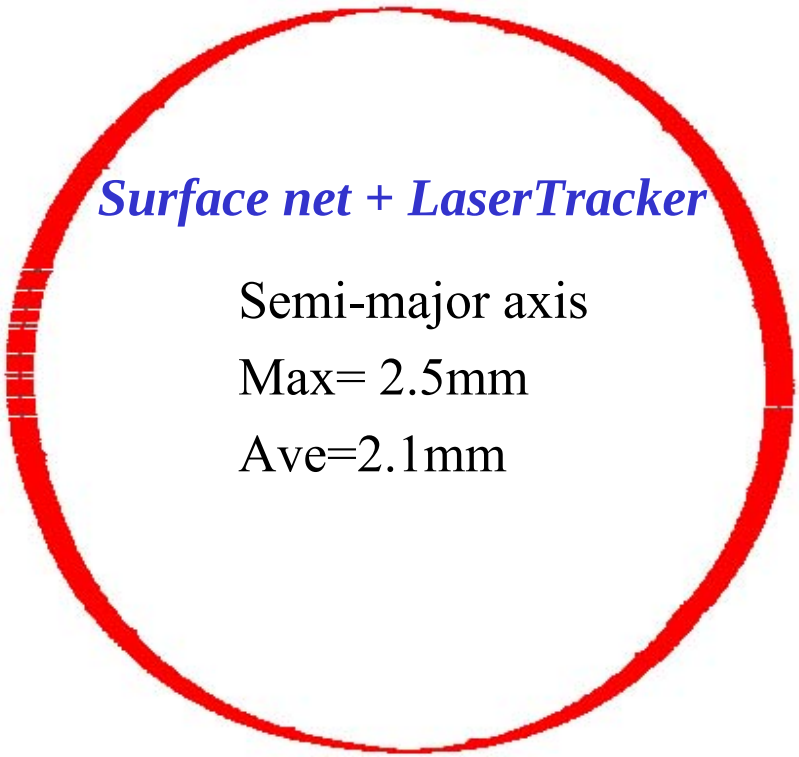
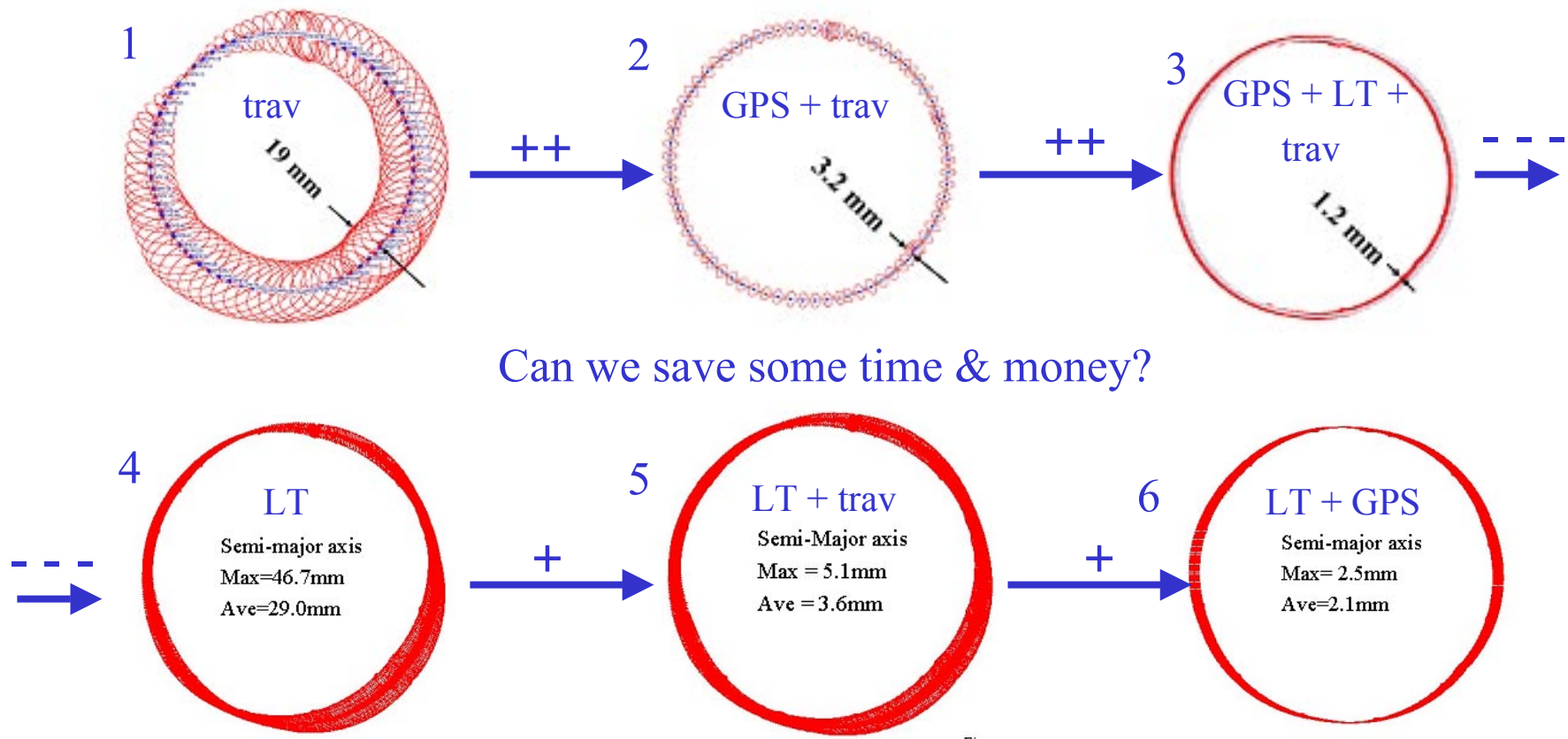


Figure 6

Network Design Evolution

design criteria = 2.5mm



Network Design Evolution

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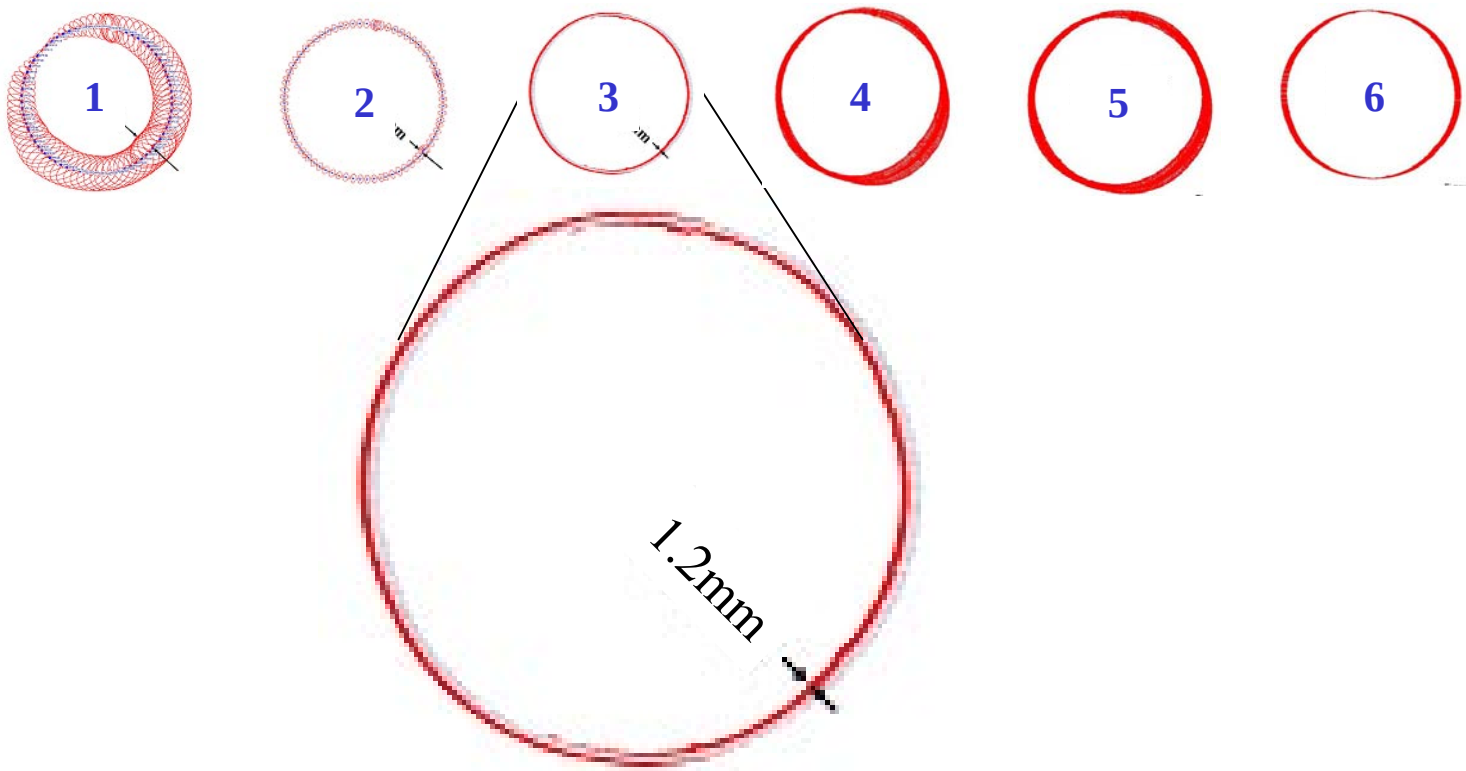
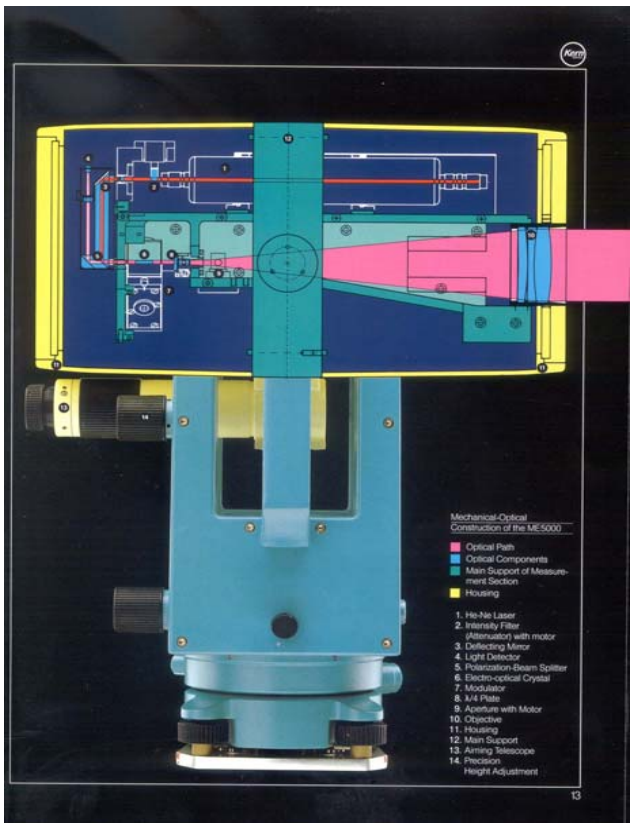
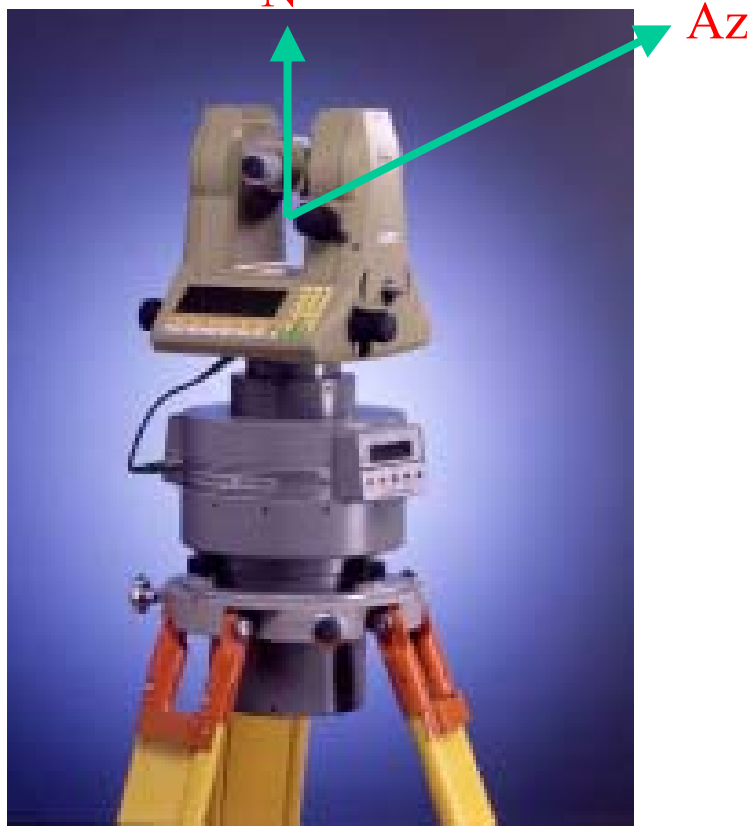


The clear winner is design #3

Surface + Traverse + LaserTracker

Distance & Azimuth Equipment





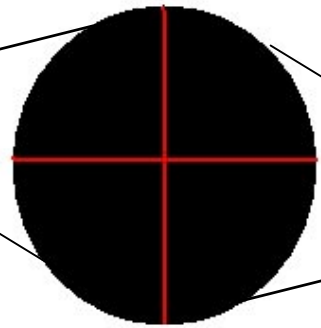
Mekometer ME5000 laser EDM

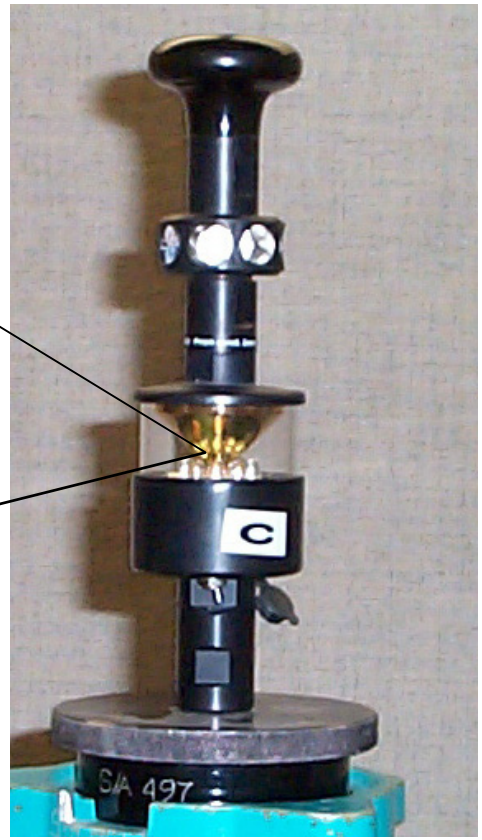
Precision: 0.2mm +/- 0.2ppm; range 20m-8km

Gyromat 2000 gyro-azimuth

Precision: +/- 3 arc-seconds

Angle Measuring Equipment





Geodimeter Robotic Total Station

Angular precision: ~ 0.25 arc-second

Autolock target

Quadrature diode emitter

Level Equipment

Leica DNA03 digital level

Precision: 0.3mm/√km

Bar code level rod

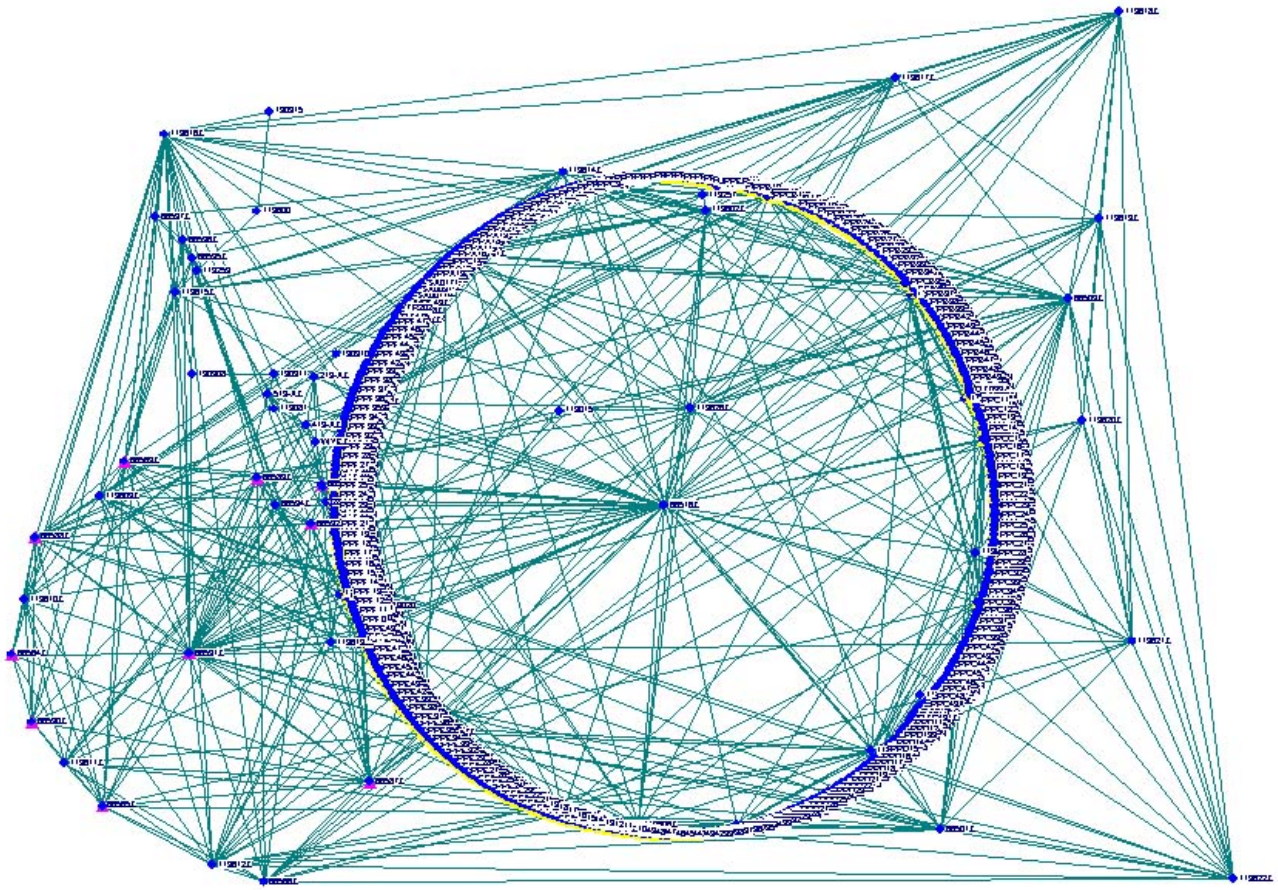
New Software

COLUMBUS* Geodetic Network Adjustment Software

**Because the world isn't flat!*

N.B. Adjustment = Gaussian fit, not chiropractic procedure

TeVnet Observation Diagram



Resources expended

- 7 staff-months planning
- 550 FTE-weeks fieldwork – ’03+’04
- 20 staff-months analyzing 2003 data
- 16 staff-months analyzing 2004 data

Body of work

- 482 Tracker setups
- 69,658 Tracker obs
- 29,498 Tracker chords
- 623 GPS baselines
- 141 Mekometer obs
- 24 Gyro-azimuth obs

- 84 Autolock angles
- 14 vertical drops
- 1035 Tunnel elevs
- 86 Surface elevs
- 1940 coordinated pts

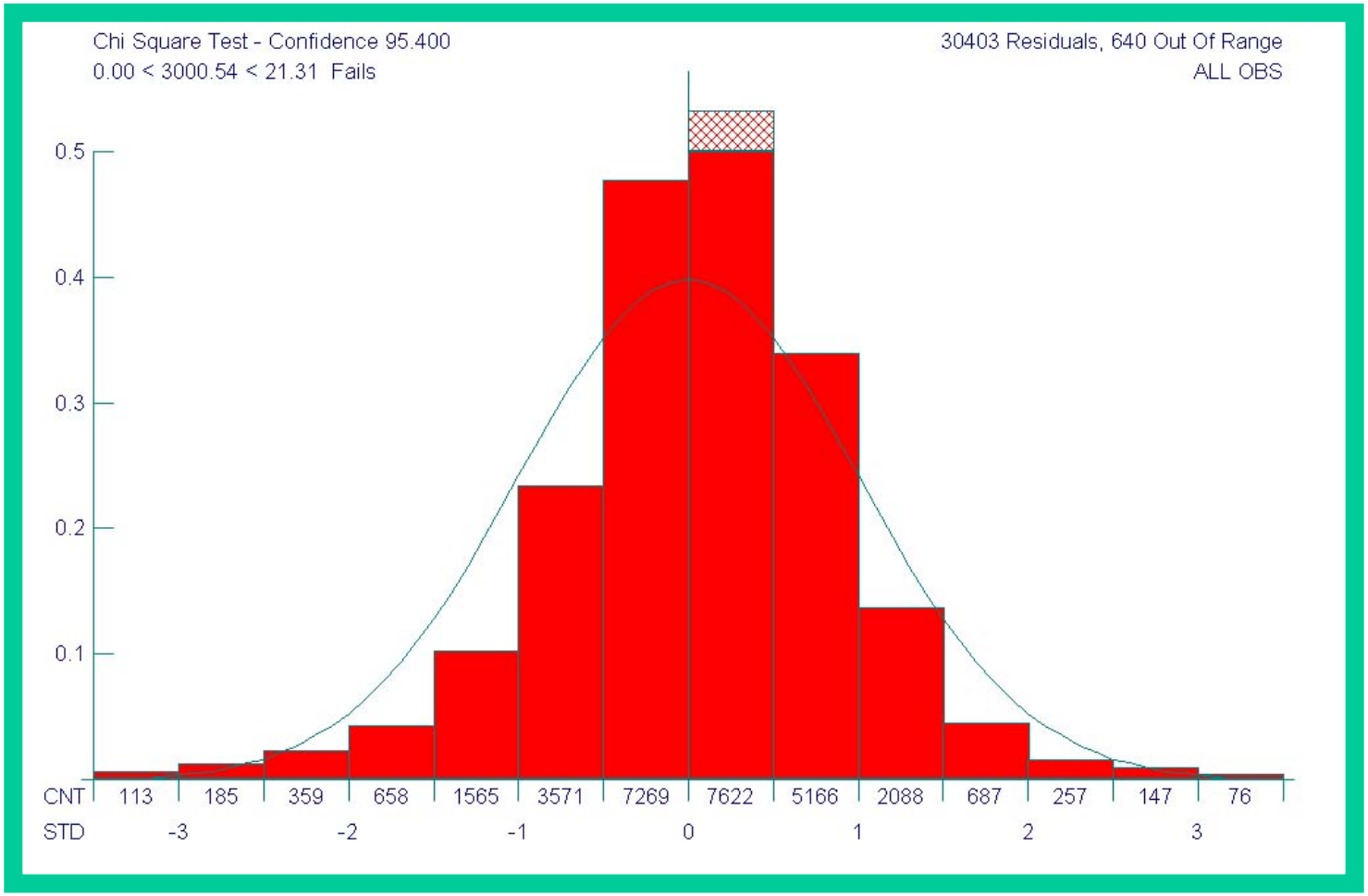
Adjustment Results

- Constrained on 10 primary site pts and local master BM
- Observations: 30,403
- DOF: 23,308
- Outliers: 145
- Rejections: 11

Global precision

- **$X_{2\sigma}$ = 0.65mm**
- **$Y_{2\sigma}$ = 0.63mm**
- **$Z_{2\sigma}$ = 0.63mm**

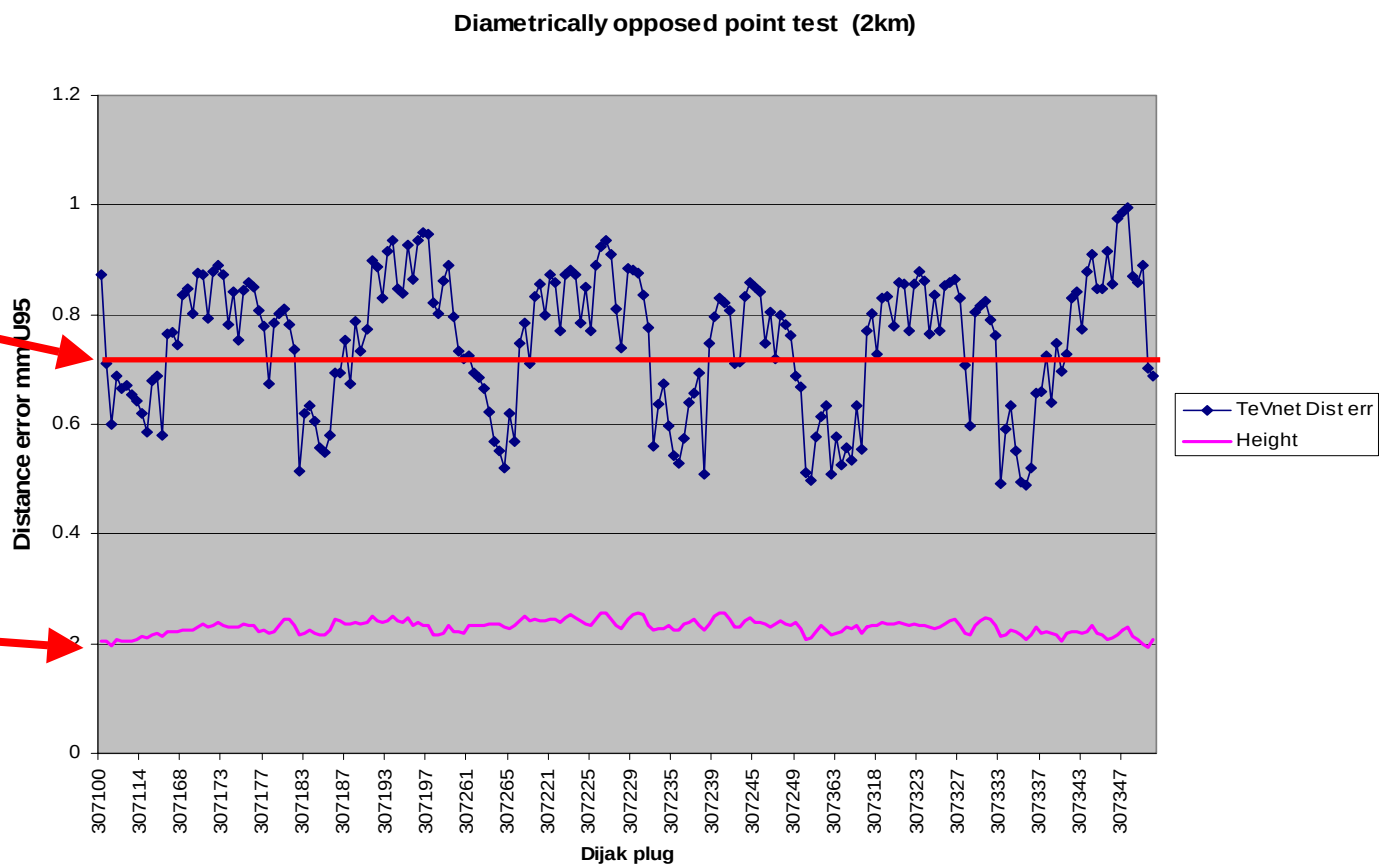
TeVnet Control Histogram 2σ



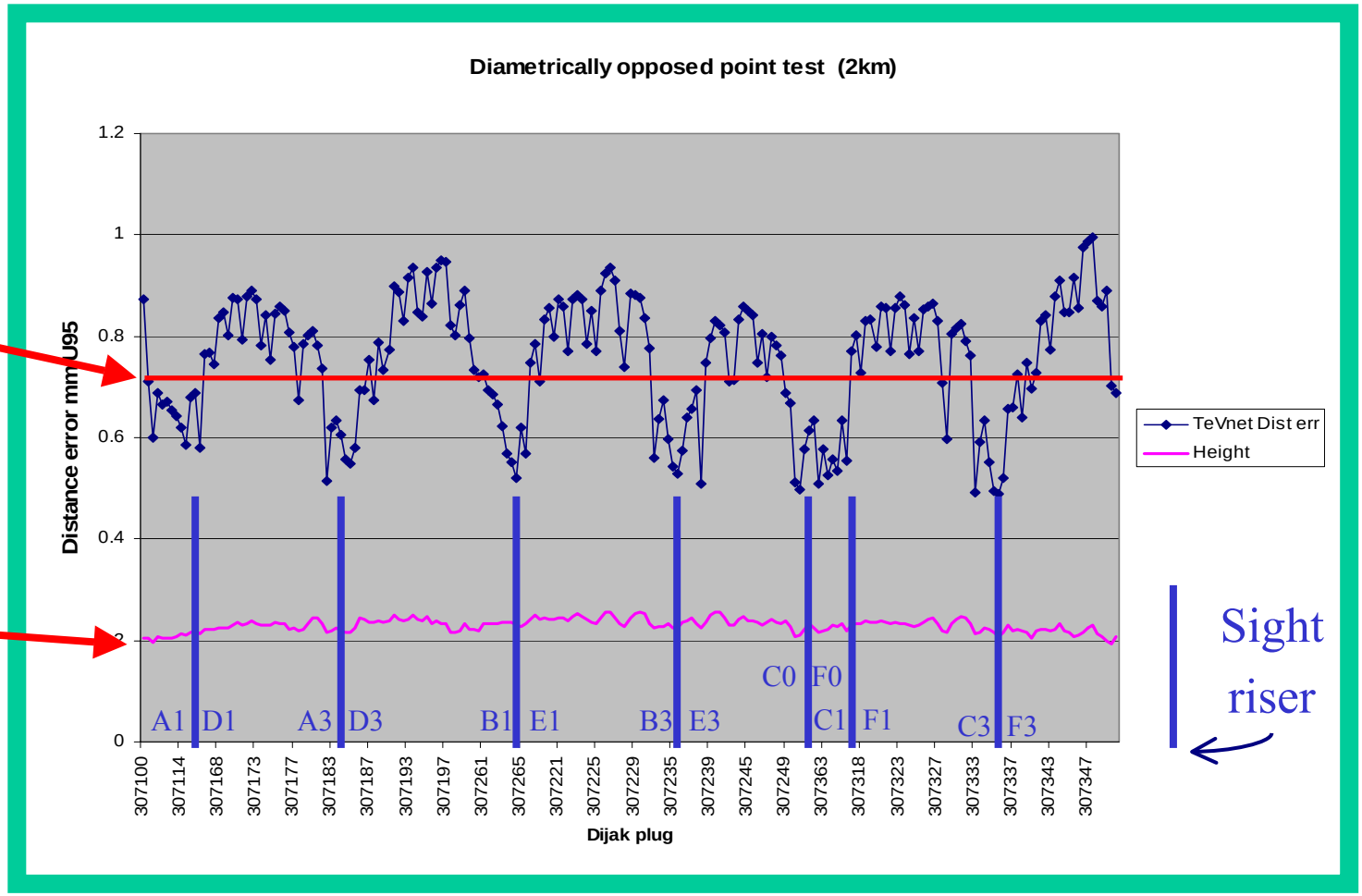
Distance Errors Across the Tev 2σ – *2km*

0.75mm Mean

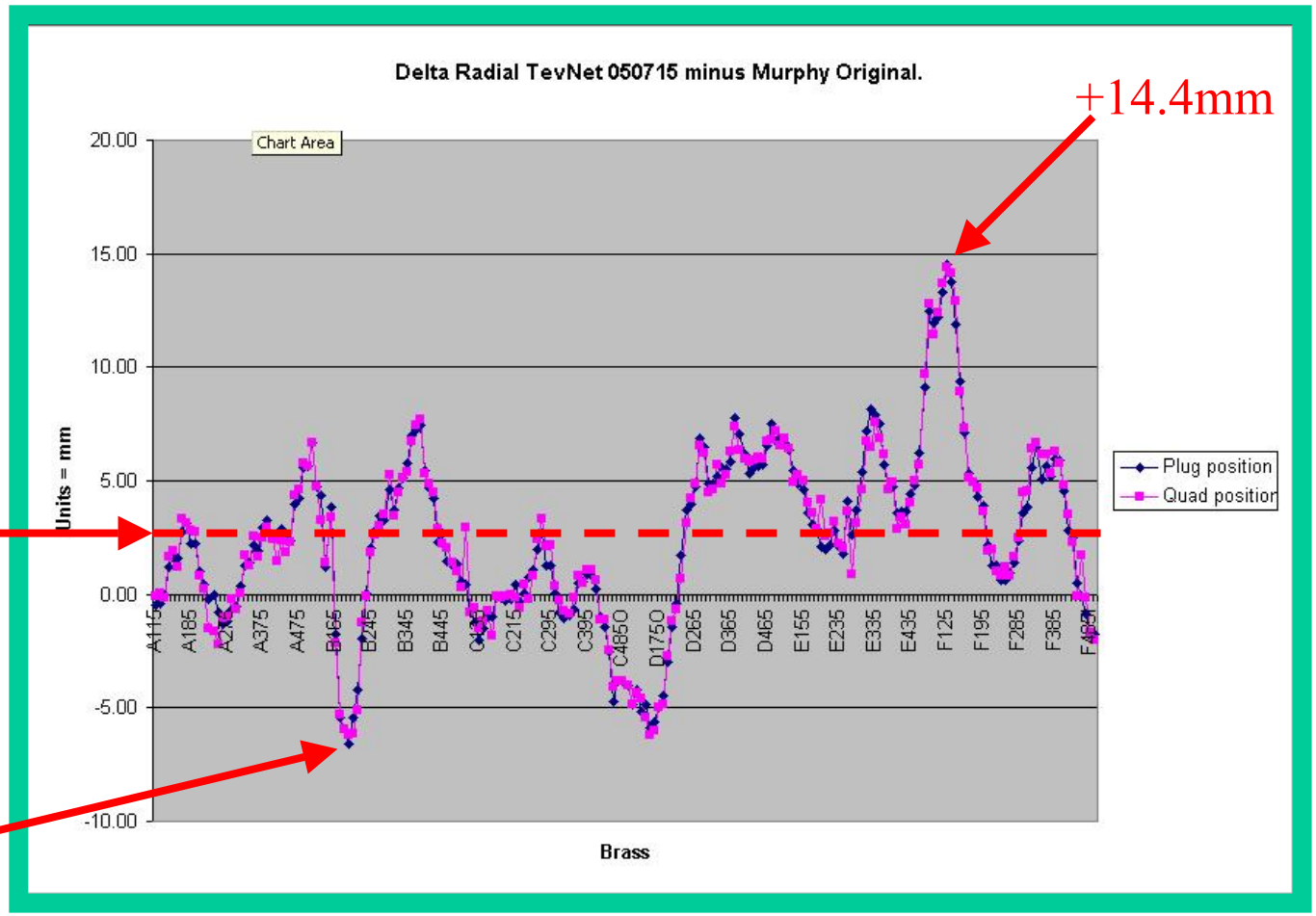
0.23mm Mean



Distance Errors Across the Tev 2σ *2km*



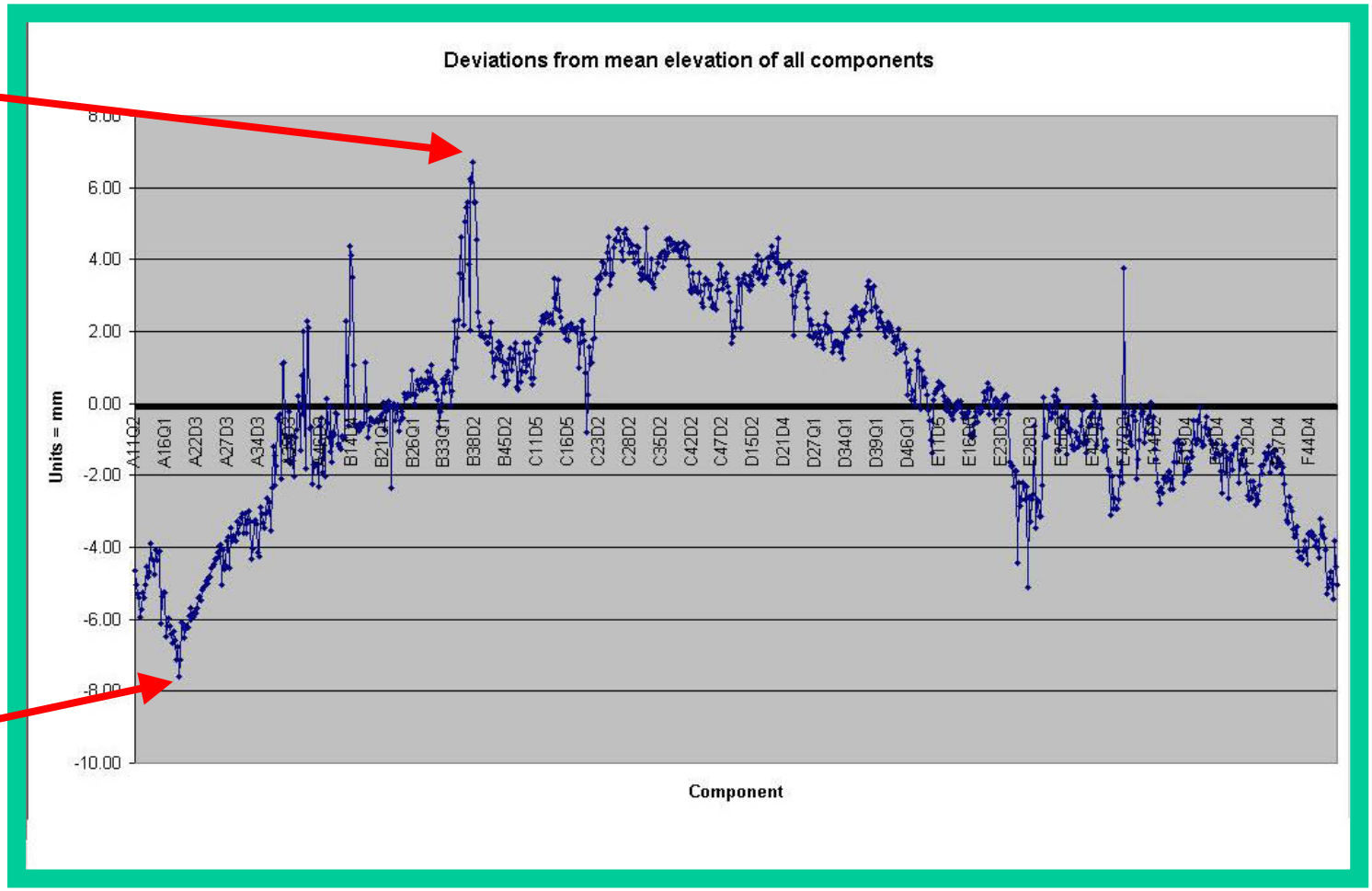
As-found radial deviation from an IDEAL Machine



As-found vertical deviation of the quads from the mean elevation

+6.7mm

-7.6mm



Mission Accomplished!

Precision across the ring:

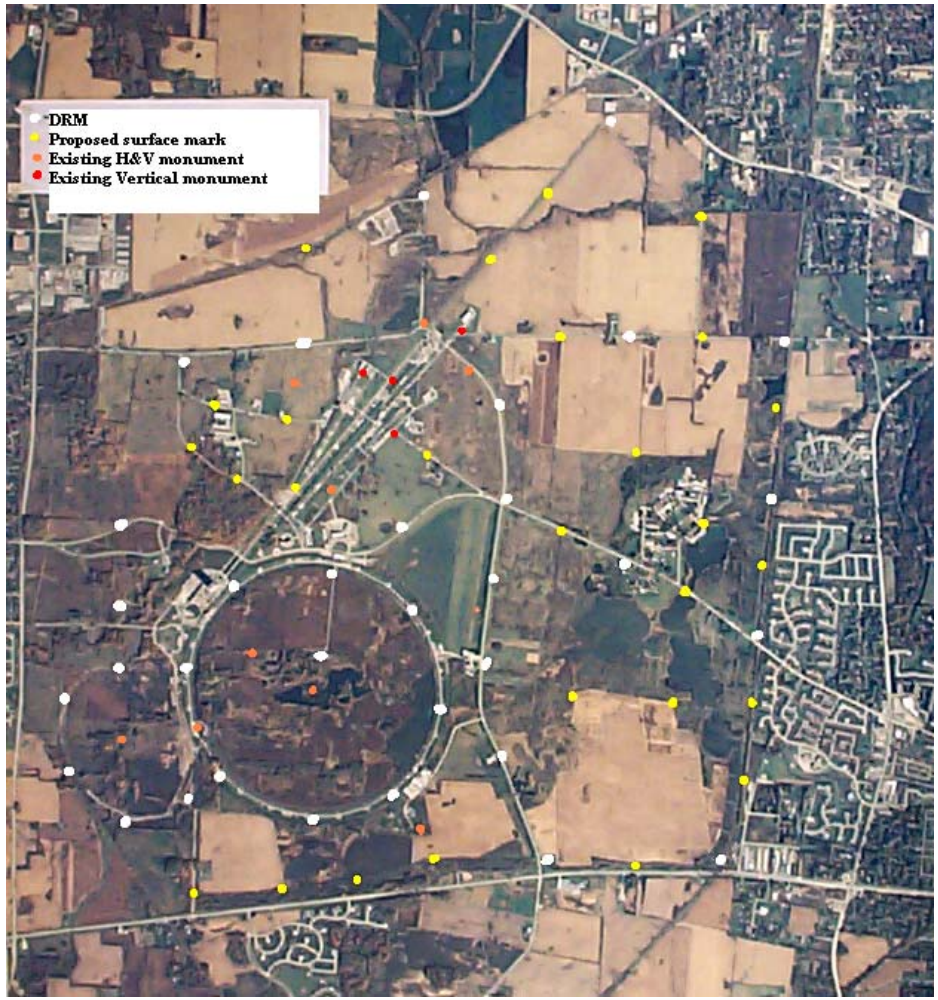
0.75mm 2σ << 2.5mm 1σ

Delivered Requested

What's next for TeVnet?

- Surface vertical network annual releveling.
- Install tunnel DRM in the Tevatron and Main Injector.
- Align the Tev with the new data?
- Revise Tracker data analysis software to eliminate derived chord usage.
- Extend the DRM network towards examining stability issues in anticipation of future projects.
- **???**

Perhaps FermiNet & ILC?



or…

Fermiville 2020?